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US Army Research Laboratory

HEaDS-UP Phase IV Assessment: Headgear Effects on Auditory Perception

by Angelique A Scharine

NOTICES

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14. ABSTRACT

Two modular helmet systems, consisting of helmet, eye, and mandible protection plus tactical communications via earmuffs (EMs), earplugs (EPs), or double hearing protection, developed under the Helmet Electronics and Display System-Upgradeable Protection program were evaluated for their effects on auditory perception. Measures of passive directional attenuation were made for the helmets alone, hearing protection alone, and in combination. The situation awareness (SA) microphones of the communications system compressed noise transmission when ambient levels exceeded 85 dB (A) so that at 110 dB (A) the noise level under the EPs was only 88 dB (A) for the highest microphone setting. For EMs, attenuation was limited to approximately 18.5 dB (A) of passive protection with additional amplification caused by the ear canal; therefore, with the microphones on the highest setting, the level under the EM at 110 dB (A) was 110 dB (A). Impulse noise attenuation for the systems was measured by presenting impulses at peak levels of 150 and 171 dB with the SA microphones turned off, on low, and on high. EPs, EMs, and double hearing protection provided impulse noise protection equivalent to the passive attenuation of the hearing protectors when the SA microphones were on.

15. SUBJECT TERMS

hearing protection; auditory situation awareness; impulse noise attenuation; directional attenuation; input-output function

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1. Introduction

This effort was conducted through the Helmet Electronics and Display System-Upgradeable Protection (HEaDS-UP) program to characterize the acoustic effects of 2 helmet and hearing protection systems in impulsive and continuous noise environments. There were 2 objectives for this testing: 1) document the protection provided against noise-induced hearing loss, specifically from steady-state and impulsive noises, and 2) document the effects of these 2 systems on hearing capabilities, specifically on the ability of a user to detect and recognize ambient environmental events.

Figure 1 shows the 2 candidate helmets, each designed to be used with a detachable mandible, eye protection, and the Selex ES Wolverine tactical communications and protection system. These devices provide radio communications, protect against unsafe levels of noise, and provide restoration of ambient hearing. The acoustic testing reported here measures their hearing protection and hearing restoration features and therefore are referred to as hearing protection devices (HPDs). The first helmet candidate (Fig. 1a), the INTEgRated Conformal Protective helmeT (INTERCPT), was developed by Revision Military. The second candidate (Fig. 1b), the Conformal Integrated Protective HEadgeaR (CIPHER), was developed by Artisent LLC (nee Artisent, Inc). The Selex Wolverine HPD components include (Fig. 1c) circumaural earmuffs (EMs) and (Fig. 1d) in-the-ear earplugs (EPs) that can be worn independently or in combination as double hearing protection. The CTX communications hub (Fig. 2) provided by Selex Communications allows the user to switch between radio-only and radio plus situation awareness (SA) microphones, allowing the user to choose between single EP, EM, or double hearing protection.

The Selex Wolverine HPD components of these systems provide passive and active protection against unsafe levels of noise. Passive protection comes from the attenuation created by the EMs or EPs as a barrier to prevent transmission of sound. Although the attenuating effects of the helmets are minimal, they alter the spectral profile of the sounds reaching the ear. HPDs also alter the physical profile of the region near the ears and passively attenuate incoming sounds, reducing overall hearing sensitivity.

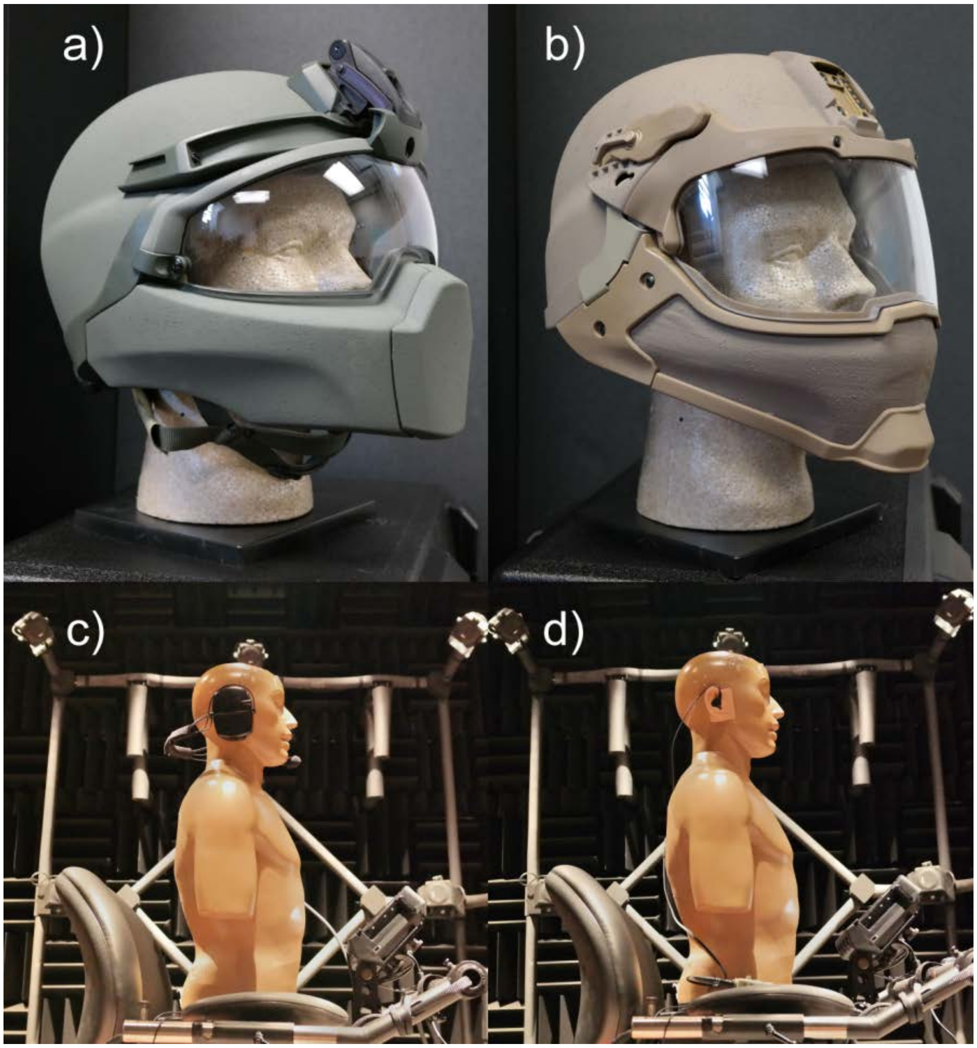

Fig. 1 System components tested: a) INTERCPT helmet, b) CIPHER helmet, c) EMs, and d) EPs

Fig. 2 Selex Wolverine CTX communications hub

Auditory SA can be restored when the HPDs are turned on because the external SA microphones transmit ambient sounds to the ear. Active protection against noise-induced hearing trauma is provided by electronically limiting sounds above approximately 85 dB (A),[1] and a shut-off is triggered by impulsive noise consistent with the US Occupational Safety and Health Administration (OSHA 1981), the National Institute for Occupational Safety and Health (NIOSH 1998), and military standard (MIL-STD-1474D 1997) requirements for hearing protection for levels at or above 85 dB (A).

Because the helmets and HPDs alter and attenuate the sound reaching the ears, we measured the attenuation of each helmet, HPD type, and combination thereof as a function of frequency and angle. Measurements were made for 2 levels of amplification and 2 levels of ambient noise to determine the sound pressure levels under the HPD as a function of these variables.

To characterize the function of the pass-through microphones and determine the extent to which the shut-off and compression mechanisms protect against high levels of noise, input-output functions were measured for both forms of the HPD and at each amplification setting.

HPDs with active SA microphones must shut off transmission quickly in response to impulsive noises such as weapon fire. To ensure that the systems are shutting off in response to impulse noise, measurements were made of the noise level under the HPD with the SA system turned off (passive), turned on to the lowest setting, and turned on to the highest setting.

2. Directional Passive Attenuation

The placement of a helmet or HPD over the ears will passively attenuate ambient sounds. To describe the effects of the helmets and HPDs on auditory sensitivity, passive directional attenuation was measured for the EMs, EPs, double hearing protection, and each of the helmets, worn both alone and with the EPs.

2.1 Facilities and Instrumentation

2.1.1 Research Facility and Loudspeaker

The test signal was presented from a JBL PRX512M loudspeaker located in the corner of the US Army Research Laboratory's Environment for Auditory Research (EAR) Dome Room (Henry et al. 2009) about 3 m from the center of the room (Fig. 3).

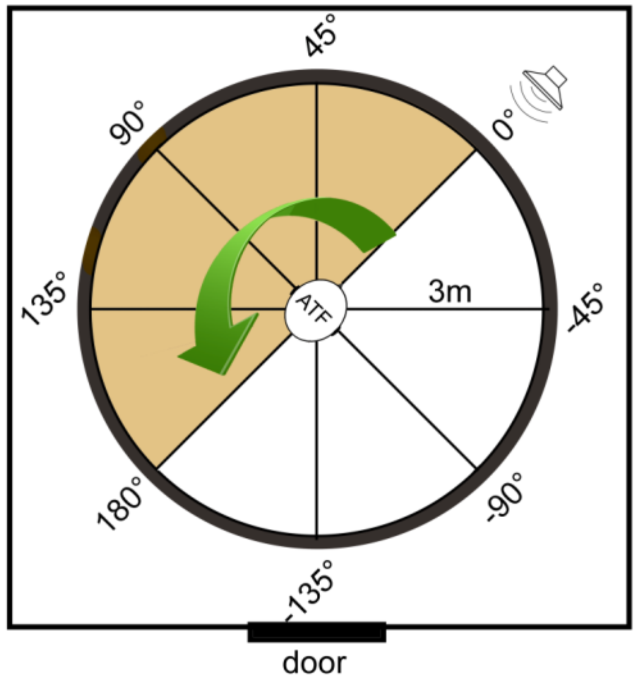

Fig. 3 Listening Laboratory and configuration of loudspeakers and auditory test fixture (ATF) during measurement of steady-state noise attenuation

2.1.2 Noise Signal

The test signal was pink noise presented at both 80 and 100 dB (A) as measured with a Brüel and Kjær Sound Level Meter Type 2226 held at the location of the ATF. These 2 levels were chosen because the 80 dB (A) is below the level for which the SA microphones are required to attenuate noise and 100 dB is high enough to trigger the noise-reduction features.

2.1.3 ATF

A G.R.A.S. Hearing-Protector Test Fixture Type 45CA, fitted with IEC 60711 ear simulators and molded pinnae, was positioned in the center of the room and used to record the test signal. This ATF is not meant for testing helmet attenuation; it was designed for hearing protectors. Therefore, it was modified to create a head shape by cutting a hole to the shape of the ATF in the center of a Styrofoam manikin head. The ATF was then protected using a layer of cellophane wrap and inserted into the manikin head. The head was then sealed to the ATF using thumbgum (see Fig. 4).

Fig. 4 Modifications of the G.R.A.S. Hearing-Protector Test Fixture Type 45 CA used to accommodate helmet testing. ATF inserted into the manikin head (left). View with thumbgum used to seal the manikin to the ATF (right).

2.1.4 Analog to Digital Conversion

An Echo Audiofire 12 recording interface, set to a sampling rate of 192 kHz, was used for analog to digital conversion and to transmit the signal to a laptop computer where it was recorded using Adobe Audition 3.0.

2.2 Variables

There were 5 independent variables investigated, as shown in the following Table: 1) helmet/HPD condition, 2) azimuth angle (0°, ±45°, ±90°, ±135°, 180°), 3) presentation level [80 and 100 dB (A)], 4) SA microphone setting (off, on low, and on high), and 5) frequency. The helmet/HPD conditions were: a) CIPHER, b) CIPHER + EPs, c) CIPHER + EMs, d) INTERCPT, e) INTERCPT + EPs, f) INTERCPT + EMs, g) EPs, h) EMs, and i) double (EMs worn with EPs) hearing protection.

Table   Independent variables and levels for measuring directional passive attenuation

Independent Variables	Helmet/HPD	Azimuth Angle (°)	Presentation Level	SA Microphone Setting	1/3 Octave Frequency (Hz)
a	CIPHER	0	80 dB (A)	Off	32
b	CIPHER + EPs	±45	100 dB (A)	On low (L1)	40
c	CIPHER + EMs	±90	. . .	On high (L7)	50
d	INTERCPT	±135	. . .	. . .	63
e	INTERCPT + EPs	180	. . .	. . .	. . .
f	INTERCPT + EMs	. . .	. . .	. . .	. . .
g	EPs	. . .	. . .	. . .	. . .
h	EMs	. . .	. . .	. . .	16,000
i	Double (EPs + EMs)	. . .	. . .	. . .	20,000

The dependent variable was attenuation, defined as the difference between the signal level, as measured by the ATF, with and without the helmet/HPD. For the double hearing protection, it was assumed that for conditions requiring double protection (103 dB (A) or higher), the SA microphones would not be turned on, and therefore this condition was not tested at 100 dB (A). It was also assumed that the helmet effects would remain constant between the 2 presentation levels so that the main effect would be due to the amplification of the headset, so this combination was only measured for the 80-dB (A) condition. For the INTERCPT condition, it was not possible to achieve a good seal for the EMs under the helmet; therefore, no data is reported for the INTERCPT with EMs.

2.3 Procedures

A G.R.A.S. 42AA sound calibrator with an adapter that allows it to be coupled to the ATF was used to generate a signal of 250 Hz at 114 dB. This 114-dB signal was recorded through each channel (left and right ears) of the testing system.

The pink noise test signal was played continuously from the loudspeaker. Recordings of 5-s duration were obtained from the microphones in the ATF in 1 of the 5 angular orientations in the right hemisphere. Between recordings, the experimenter rotated the ATF to position it in the new orientation. This process was completed once without headgear and 3 times for each of the helmet/HPD conditions. When measuring the levels under HPDs, after fitting the headset and making the first measurement at 0°, the levels were checked to ensure that the difference in level between the right and left ears was no greater than 10 dB. If the difference was greater than 10 dB, the HPD was refitted until this criterion was met. In this way, a good fit was ensured. However, despite many attempts, we were unable to meet this criterion for the INTERCPT worn with the mandible and EMs, possibly because the helmet dislodged the EMs from placement.[2] In this case, measurements were not completed.

The bare-head ATF recordings served as reference measurements for each of the helmet/HPD conditions. Figure 3 shows the position of the loudspeaker and the angles used. Although sounds were presented only from the right hemisphere relative to the ATF, it is reasonable to assume symmetry. Therefore, since recordings were made from ATF ears (left and right channels) simultaneously, it can be assumed that the measurement taken from the left ear when the ATF nose is pointed to +45° is approximately the same as would be obtained from the right ear when the ATF nose was pointed to –45°. Therefore, with each noise presentation, directional attenuation data was obtained for a pair of angles (0°, ±45°, ±90°, ±135°, 180°) allowing representation for directional attenuation for the full 360° horizon. These measurements were repeated 3 times to account for variability due to fitting the helmet/HPD.

2.4 Data Analysis, Results, and Discussion

Each set of directional recordings (3 × helmet/HPD × azimuth × SA microphone setting × presentation level) was processed using a custom MATLAB algorithm to compute the levels for each component octave and 1/3 octave band. This was also done for the reference set recorded with no helmet/HPD. A-weighting was then applied and the A-weighted 1/3 octave, octave, and overall levels were obtained. A-weighted values were used for all analyses reported here. For each helmet/HPD, directional attenuation was calculated by computing the reduction in the overall A-weighted signal level when the device was in place compared with the level in the bare fixture. Attenuation, as a function of 1/3 octave and octave band frequency was then calculated in the same manner.

2.4.1 Broadband Attenuation

The overall passive attenuation of the HPDs and helmets (worn without mandibles, eyewear, or HPDs) (Fig. 5) show that the CIPHER and INTERCPT compared favorably with the currently fielded advanced combat helmet (ACH). Figure 6 shows the overall attenuation of the helmet in combination with the mandible, eyewear, and HPD systems. Adding the mandible and eyewear did increase attenuation by about 1 dB. Using the SA microphones, set to the lowest gain setting, restores hearing to levels near that of the unoccluded ear, especially for the EM-based system.

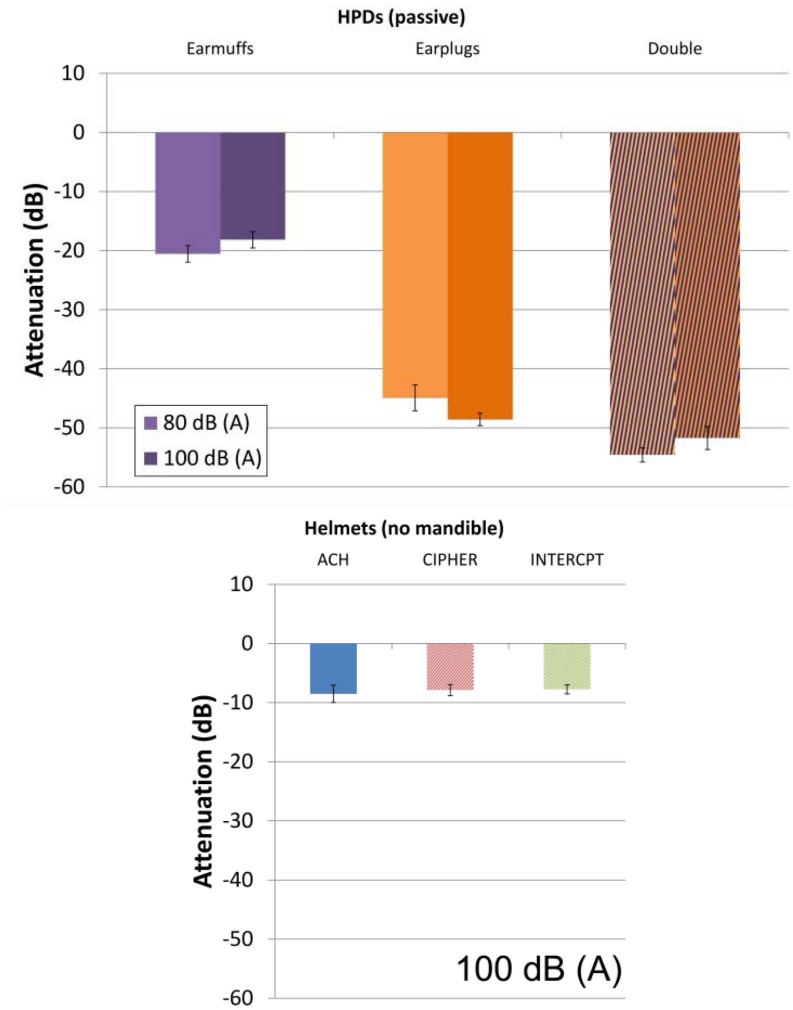

Fig. 5 Average passive attenuation as measured for each of the HPDs and each helmet (without the mandible). The attenuation of the ACH is shown for comparison. The error bars represent ±1 standard deviation.

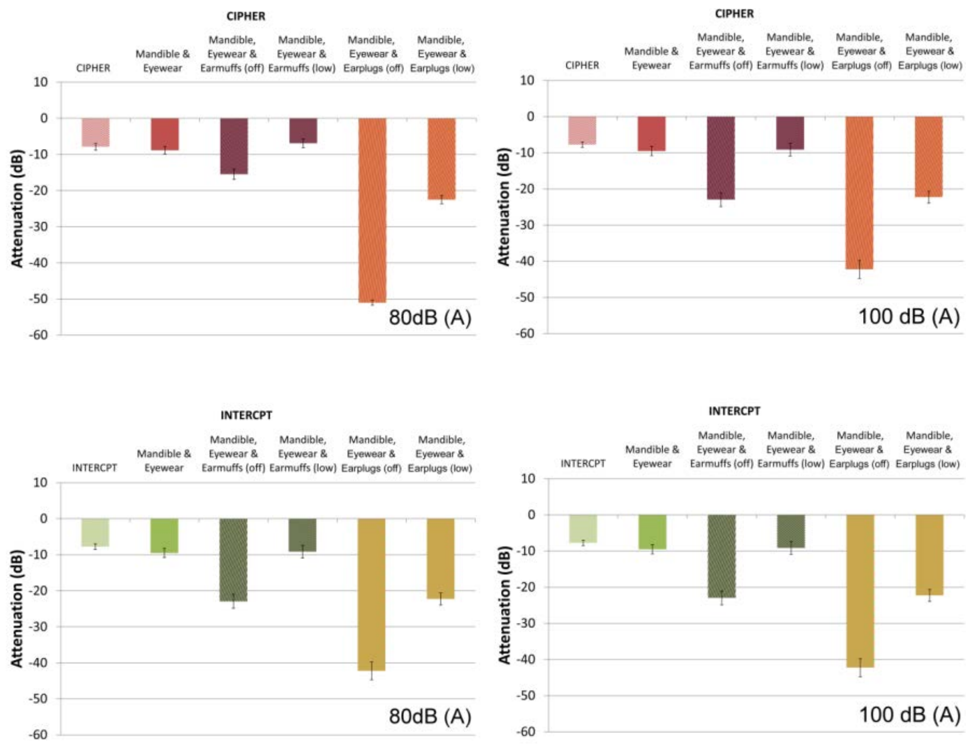

Fig. 3 Average attenuation measured for the CIPHER and INTERCPT helmets as a function of noise level, mandible/eyewear configuration, HPD worn, and SA microphone setting

The difference in measured levels for the EPs and EMs can be explained by several factors. First, the input-output measurements (described in Section 2) demonstrate that the ear canal amplifies the overall signal by approximately 12 dB relative to the external level. This amplification was not present for the EPs because they insert into the ear canal and reduce the size of the resonant cavity. This is consistent with typical[3] noise-reduction rating data for EMs and EPs. Further, our ATF measures of EP attenuation have typically been high; remember that the 40-dB limit of bone conduction will reduce the actual level of attenuation due to transmission that occurs through the bones and skull rather than through the ear canal. The increase in the amount of attenuation for the EPs compared with the EMs when the SA microphones are turned on to the lowest setting reflects both the lack of amplification by the ear canal and the increased passive attenuation of the EP.

2.4.2 Broadband Directional Attenuation

All directional measurements are shown as a function of the orientation of the ATF nose with respect to the loudspeaker as measured from the right ear of the ATF. Figure 7 shows the A-weighted noise level as measured with the ATF at each of the 8 angles as a function of frequency. Figure 8 shows the A-weighted noise levels measured with the reference microphone for each of the ambient noise conditions and as a function of frequency. The ATF measurement at 0º is shown for reference to show the transfer function of the ear canals. The differences in the spectrum and level measured by the reference microphone and the ATF reflect the spectral effects of the resonance of the ear canal of the ATF. All attenuation measures are calculated in reference to the levels measured with the ATF with no hearing protection or helmet.

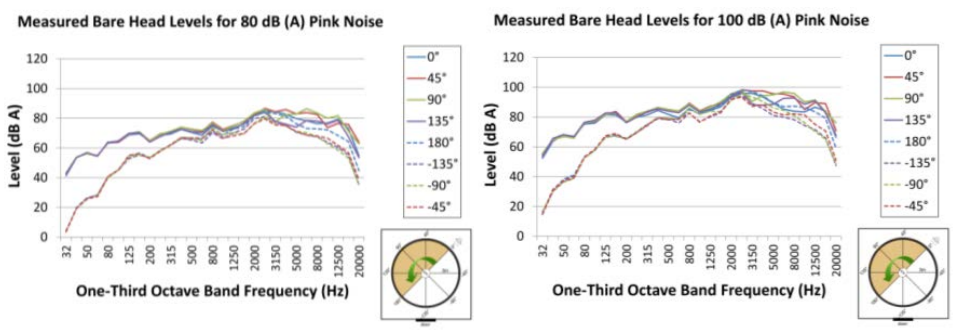

Fig. 4 Noise level measured with the ATF (at all 8 angles) when presented with pink noise at 80 and 100 dB (A)

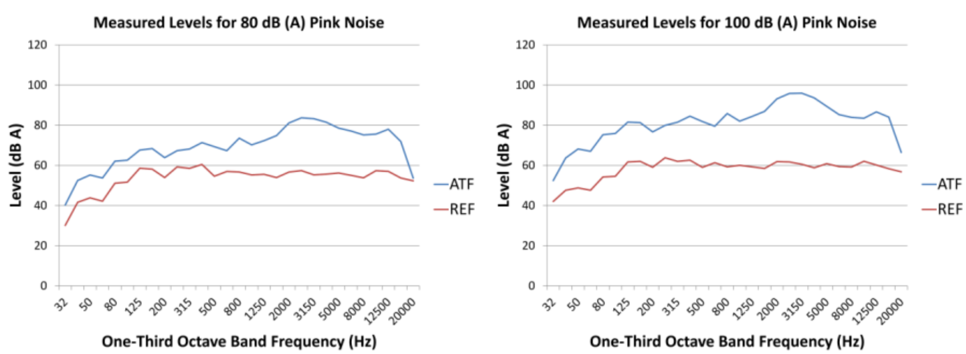

Fig. 5 Noise level measured with the reference microphone when presented with pink noise at 80 and 100 dB (A). The bare-head measurement at 0º is shown as a reference.

Figure 9 shows the passive directional attenuation as measured for the hearing protectors as a function of ambient noise level. For the most part, passive attenuation does not differ as a function of ambient noise levels; differences in the data are due to measurement variability. Figure 10 shows the directional attenuation as measured for the EMs, EPs, and double hearing protection conditions as a function of SA microphone setting and ambient noise level. For the EPs, when the ambient noise is 80 dB (A), which is below the 85 dB (A) level that should trigger safety limits, use of the SA microphones set to the lowest level restore hearing to approximately unoccluded levels. Raising the amplification setting to the highest level adds approximately 8–10 dB (a 2:1 gain). When the ambient noise is 100 dB (A), there is still some restoration from the SA microphones but still about 10 dB of amplification. For the EPs, the overall attenuation is significantly greater. When the ambient noise is 80 dB (A), use of the SA microphones restores about 20 dB of the attenuation. The difference between the lowest and highest amplification settings is about the same as for the EMs, about 8–10 dB.

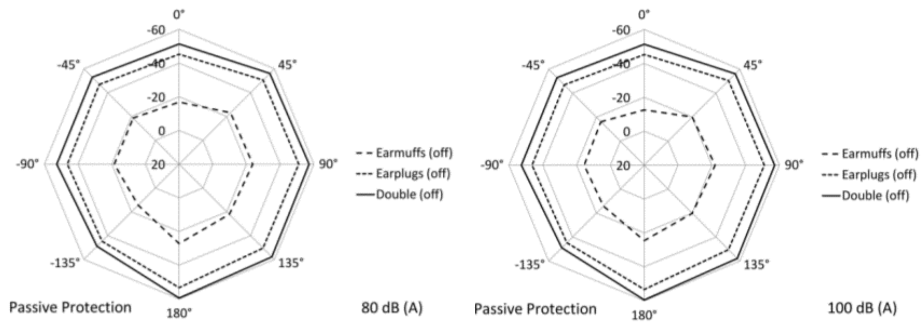

Fig. 6 Passive directional attenuation as measured for hearing protection as a function of ambient noise level. In this graph and subsequent graphs, the angles represent the orientation of the ATF's nose relative to the loudspeaker position. The values represent the attenuation measured from the right ear of the ATF relative to the bare-head condition.

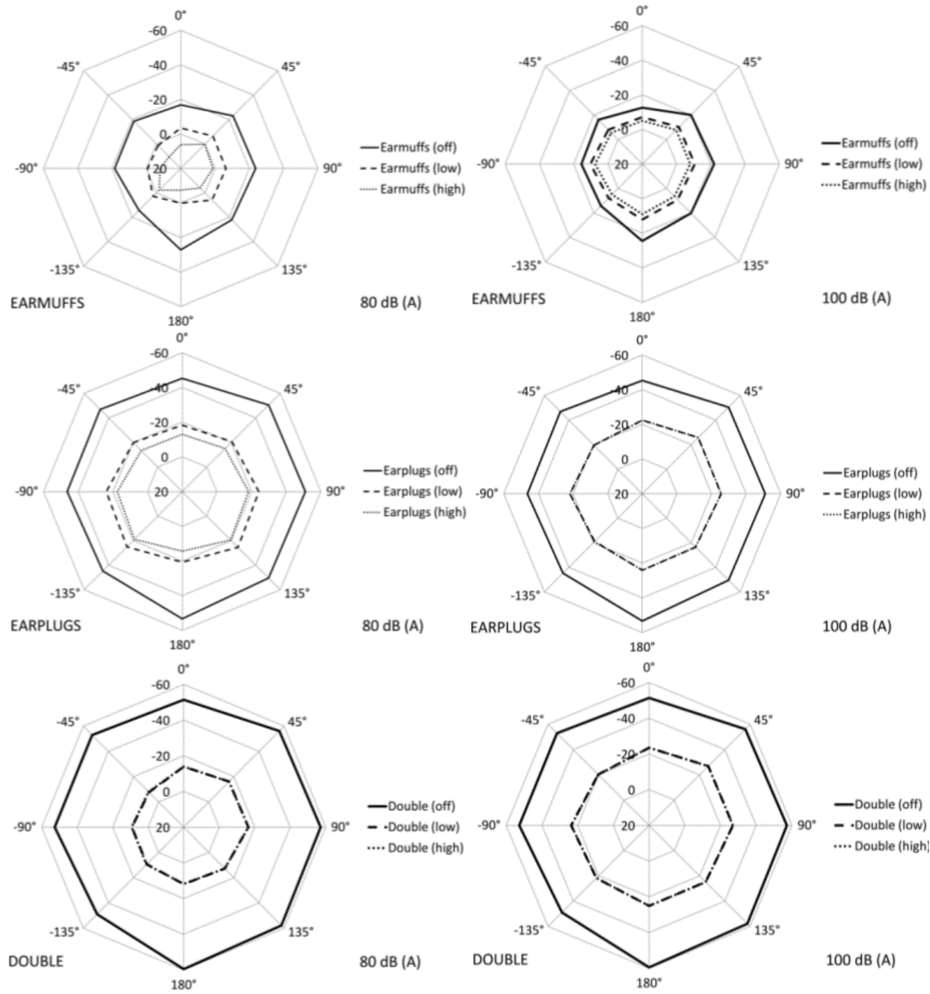

Fig. 7 Overall directional attenuation as measured for the HPDs as a function of SA microphone setting and ambient noise level

Finally, for the double hearing protection condition used in 80-dB (A) ambient noise, the SA microphones restore about 40 dB of hearing, regardless of the gain setting. Increasing the ambient noise level to 100 dB (A) reduces the degree of restoration to about 25–30 dB. Figure 11a shows the directional attenuation measured for each of the helmets as measured without the mandibles or eyewear (ME) in place. The ACH is used for reference and none of the helmets attenuate significantly. Figure 11b shows the same measurements compared with measurements for the helmets with the ME in place. Once again, the attenuation is minimal and the directional effects are similar. Figures 11c and 11d show the attenuation measured at both ambient noise levels for the CIPHER helmet worn with ME and with the EMs and EPs. These measurements were made with the SA microphones off and when set at the lowest setting.

The main effects seem to be due to the differences in HPD type (already seen when measured without the helmet) and the degree of hearing restoration provided by the SA microphones as a function of ambient noise setting. There are also small differences in the absolute level of passive attenuation measured, which may be due to the difficulty of maintaining a good seal under the helmet while positioning it. Given that the measured levels are above the 40-dB bone conduction threshold, it is likely that these are not important. Similarly, Figures 11e and 11f show the directional attenuation measured at both ambient noise levels for the INTERCPT helmet worn with ME and with the EPs. Unfortunately, it was not possible to get the EMs to stay in place to obtain measurements under the helmet that are required according to the criterion of achieving measured levels within a 10-dB difference for the right and left ears. Measured levels with the EPs are similar to that found for the CIPHER helmet.

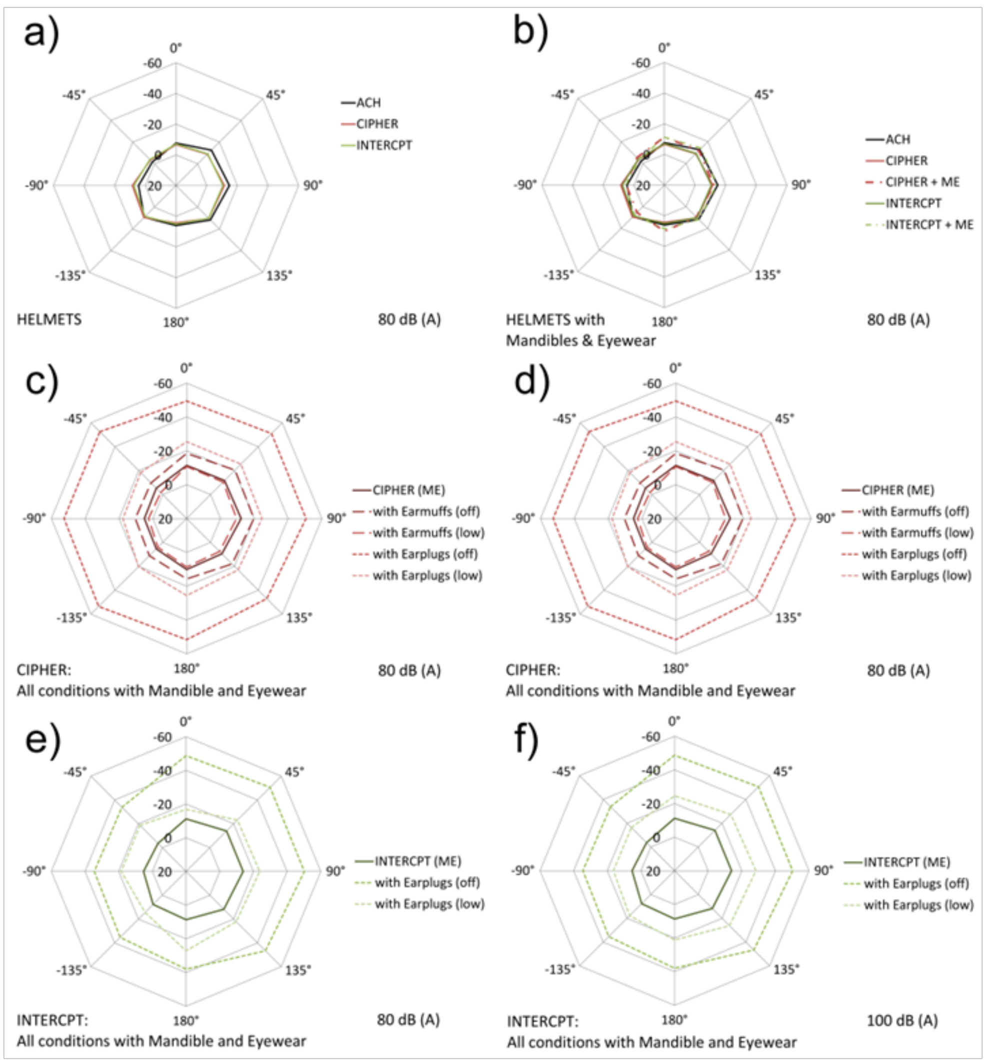

Fig. 8 Overall directional attenuation as measured for the helmets as function of SA microphone setting and ambient noise level

There is a difference between the ways that the SA microphones restore hearing depending on whether the EMs or the EPs are used. Figure 12 shows the amplification of the SA microphones as a function of frequency and amplification setting for the noise presented at 0° relative to the nose of the ATF for both ambient noise levels. This was computed by comparing the levels measured with the SA microphones off, on low, and on high. The EPs do not amplify the frequencies above about 8 kHz, and amplification is reduced further for the 100-dB (A) ambient noise condition. To some extent this is logical, as the amplification is targeted to the region that the ear canal amplifies for the EMs. In contrast, the EMs amplify the high frequencies more, perhaps to compensate for noise leakage and increase the intelligibility of face-to-face speech communication. Since the 2 headset types have independent connections, this feature is likely by design.

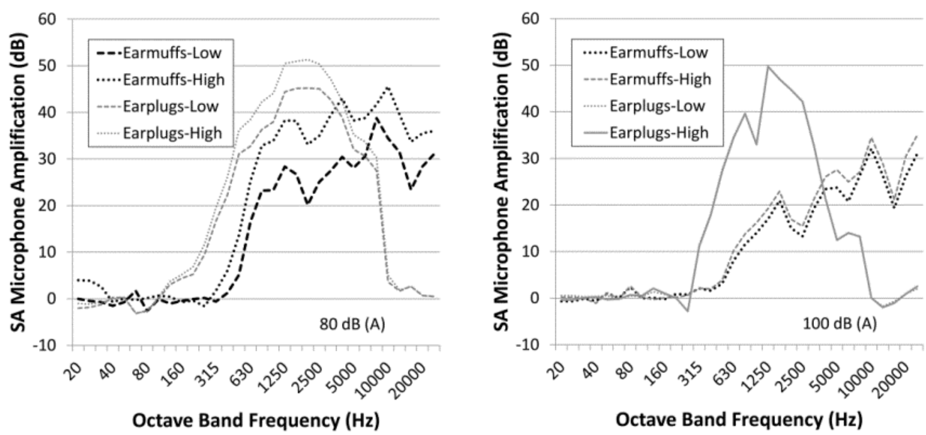

Fig. 9 SA microphone amplification as measured at 0° for each of the ambient noise conditions

2.4.3 One-Third Octave and One-Octave Directional Attenuation

Figures 13–18 show the attenuation of the helmet/HPD conditions as a function of 1/3-octave band frequency for 3 angles [0°, ±90°, and 180°] for both ambient noise levels. In these graphs the convention is that dashed lines represent attenuation measured for the left side and dots represent the 180° position. These are measures of attenuation rather than of absolute level, so the directional effects that would be observed for the bare head have been subtracted out. Much of the minimal attenuation observed for the helmets alone occurs in the frequency range above approximately 1,000 Hz. These higher frequencies contain the monaural cues that are responsible for localization, especially for distinguishing whether sounds come from the front or the rear and for the estimation of elevation. The INTERCPT appears to amplify lower frequencies coming from the opposite side of the helmet. For the front and rear angles, a peak in amplification can be observed for the CIPHER helmet near 300 Hz, such that sounds are amplified by 5–8 dB. At around 450 Hz, the CIPHER helmet seems to show a local notch in amplification. This pattern was not observed for the INTERCPT helmet. For the most part, differences in the attenuation of the different helmets and helmet/HPD configurations as measured across the frequency spectrum can be described by differences in overall attenuation and whether or not the SA microphones were in use. For all helmet/HPD conditions, there is some variability in the attenuation achieved at the 1/3-octave level of resolution that may drive differences in subjective estimates of performance and localization effects.

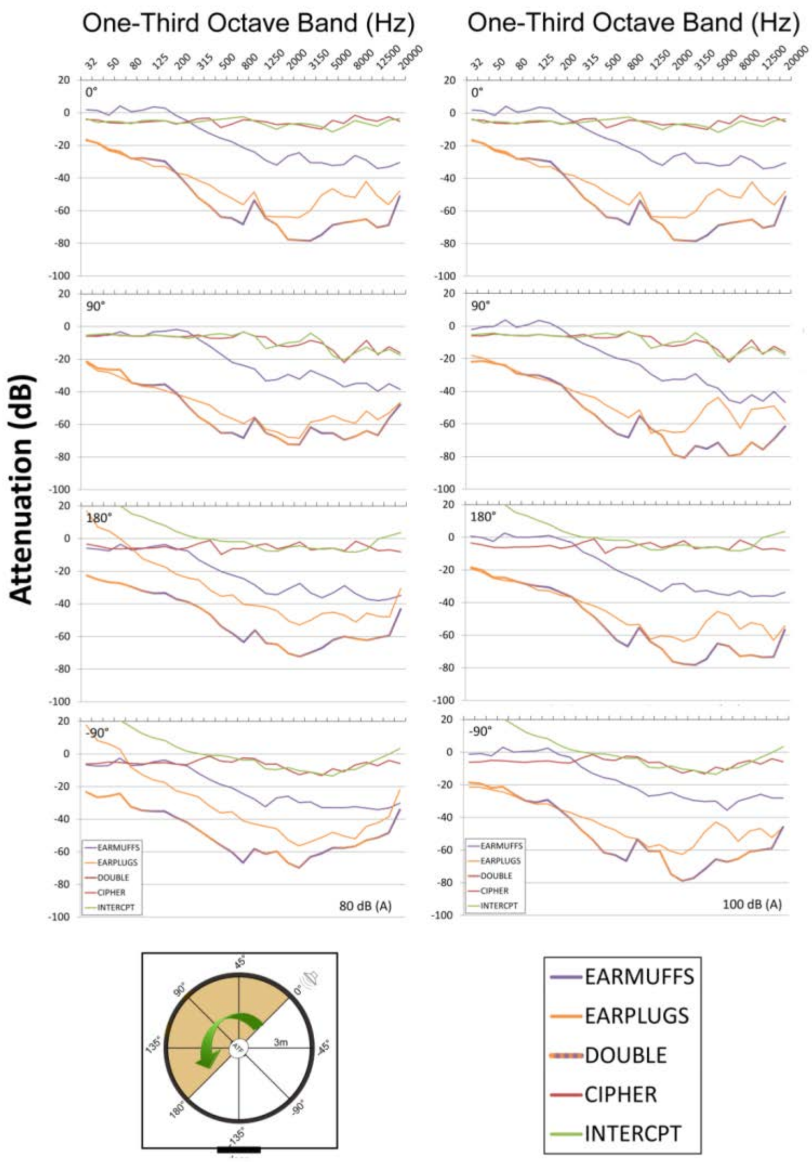

Fig. 10 Attenuation of each helmet and hearing protector as a function of 1/3-octave frequency band at 4 measurement angles. The schematic indicates the relative position of the loudspeaker with respect to the ATF ear and microphone for each of the graphs shown.

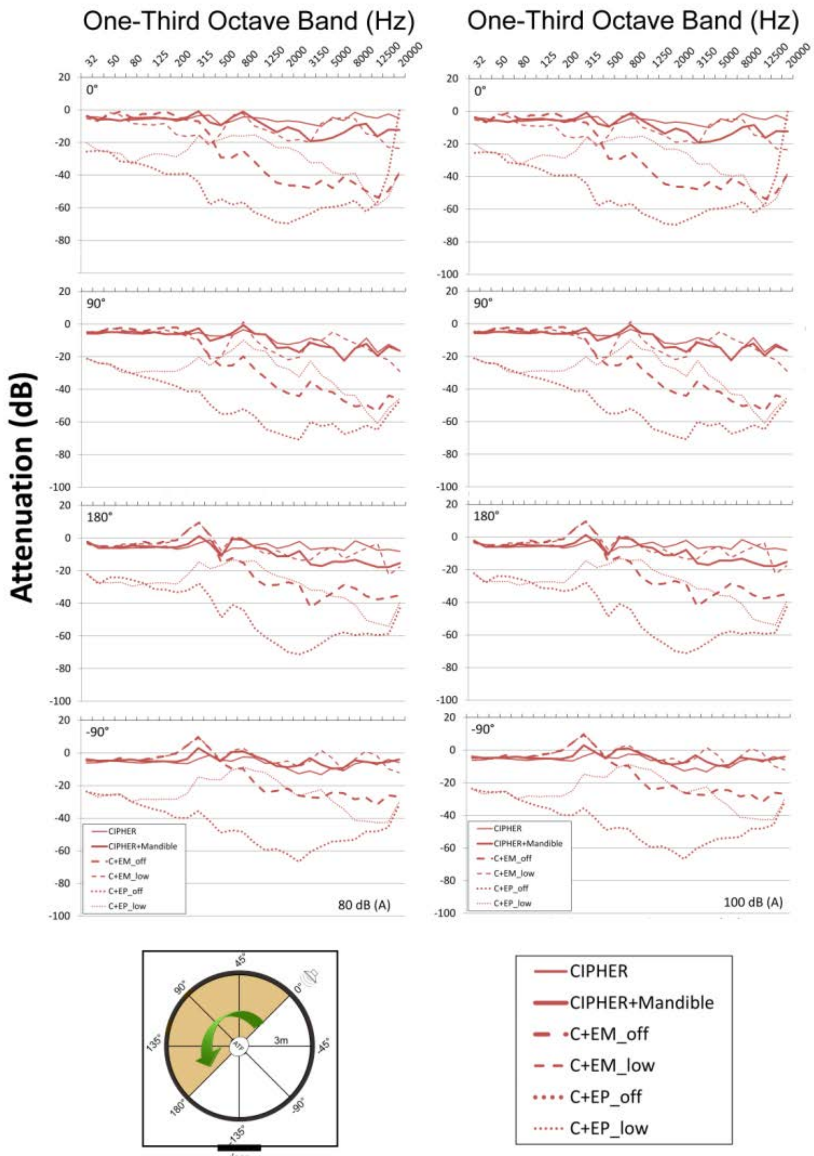

Fig. 11 Attenuation of the CIPHER helmet worn in its various configurations shown as a function of 1/3-octave frequency band for 4 angles

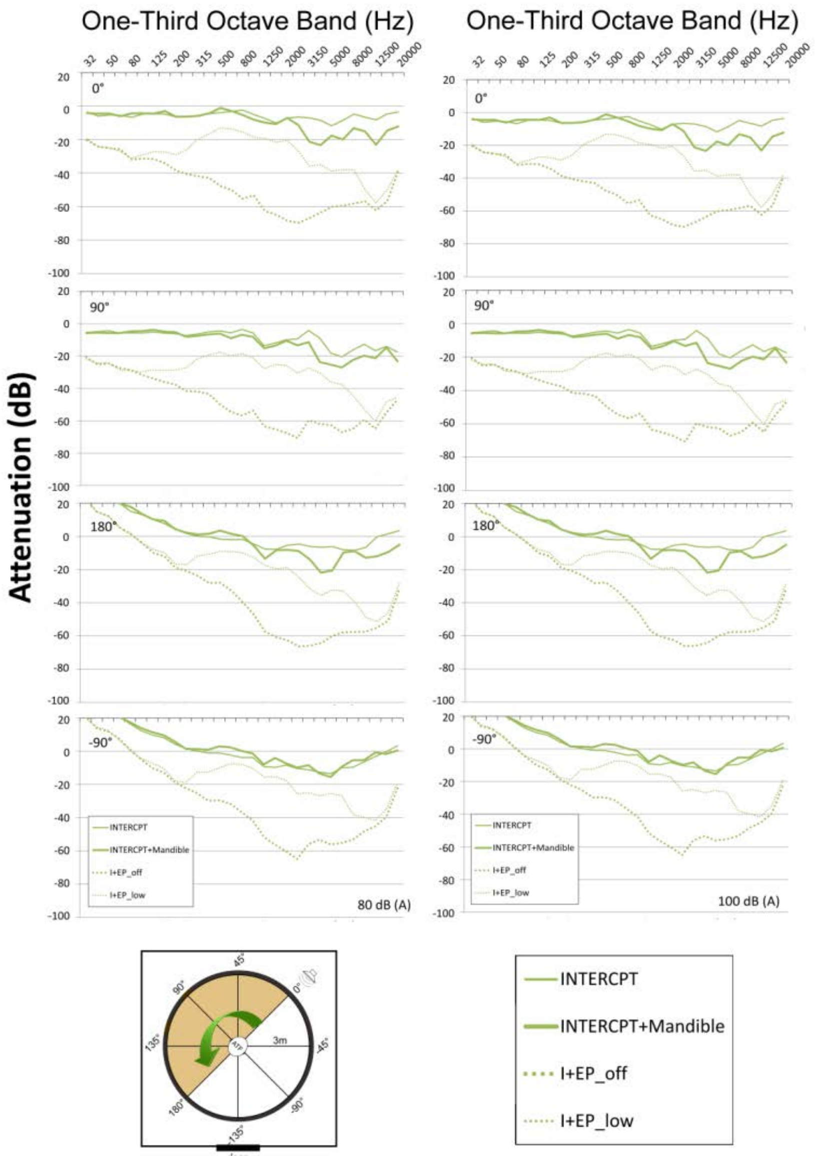

Fig. 12 Attenuation of the INTERCPT helmet worn in its various configurations as a function of 1/3-octave frequency band for 4 angles

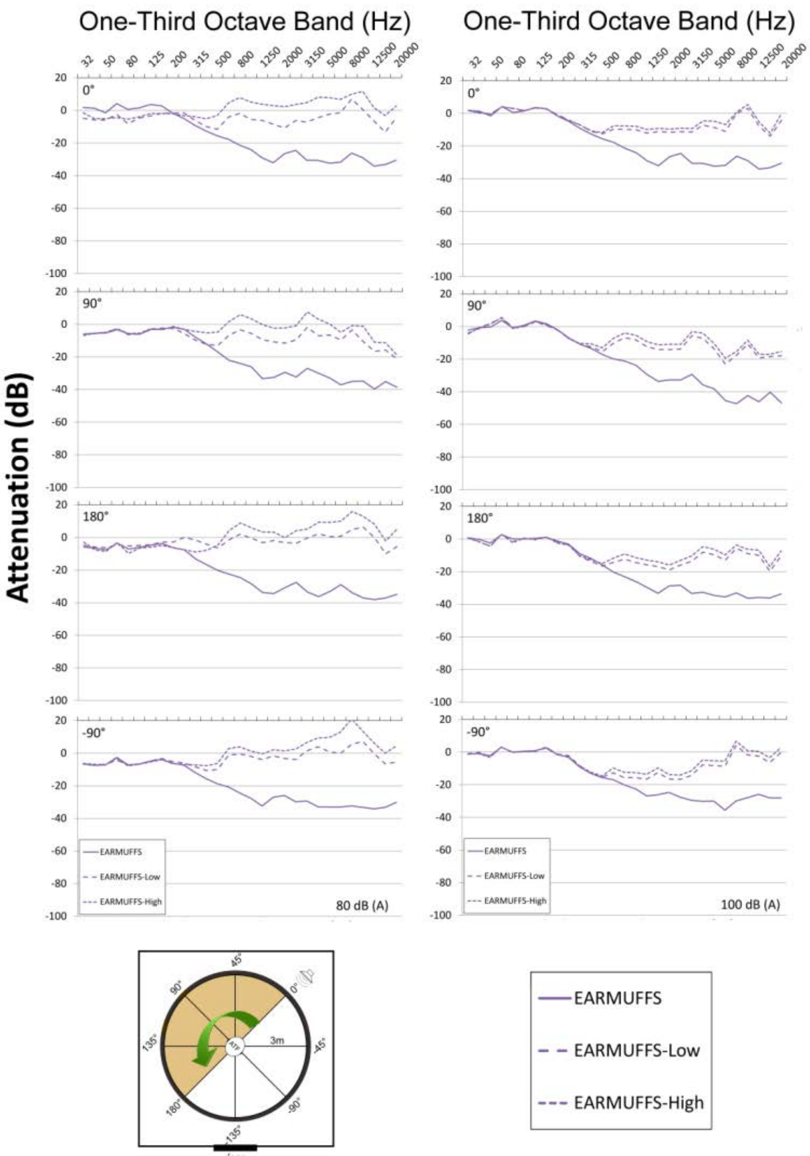

Fig. 13 Earmuff attenuation for 3 SA microphone settings as a function of 1/3-octave frequency band for 4 angles

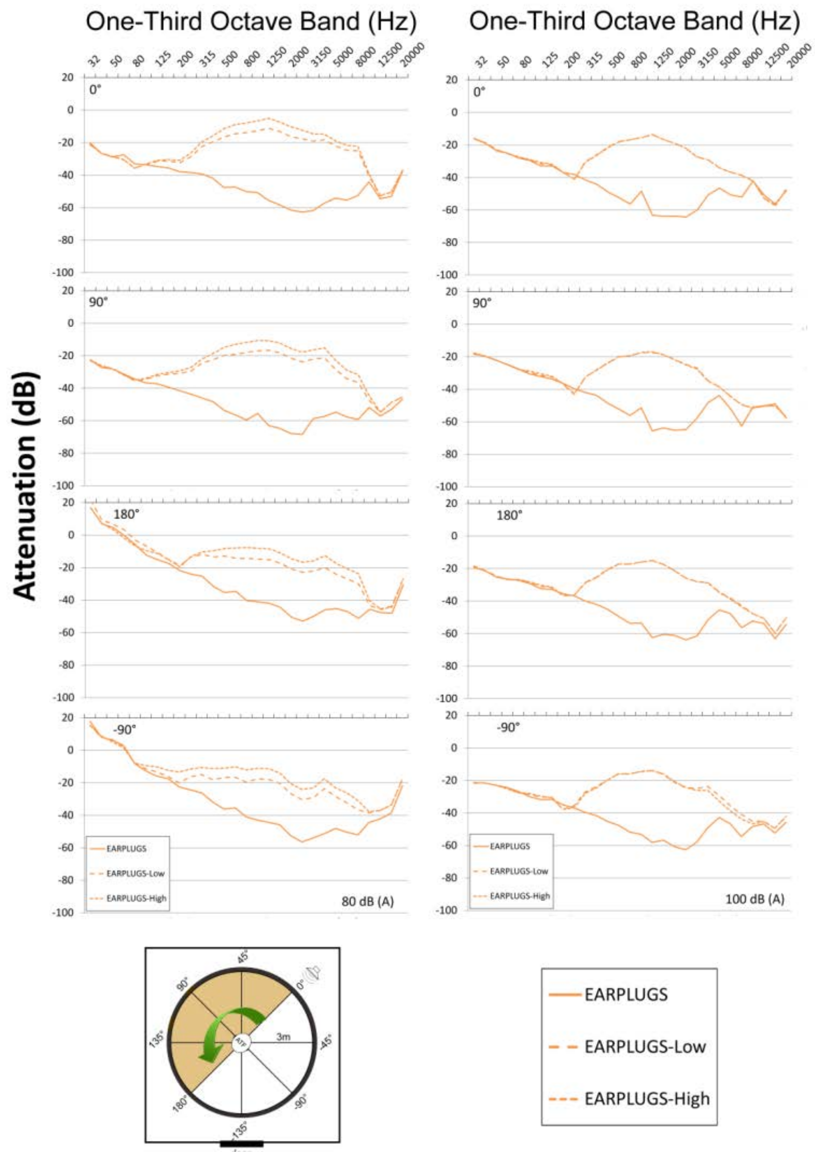

Fig. 14 Earplug attenuation for 3 SA microphone settings as a function of 1/3-octabe frequency band for 4 angles

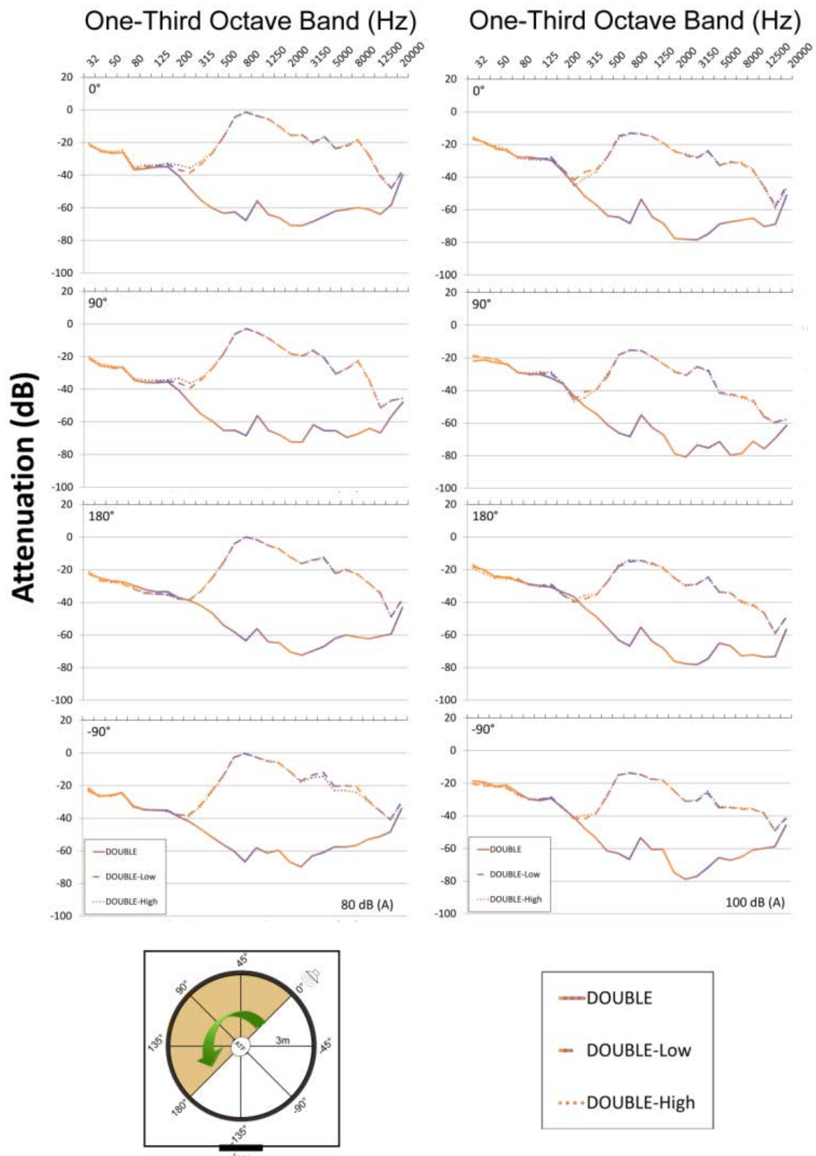

Fig. 15 Attenuation measured with double hearing protection for 3 SA microphone settings as a function of 1/3-octave frequency band for 4 angles

3. SA Microphone Transmission

The HPD and Selex communications hub are designed to compensate for the passive attenuation of the helmet and HPD and provide SA via microphones located on the EMs that transmit ambient sounds to the earphones in the device. When the ambient noise levels are below dangerous levels [approximately 85 dB (A), (OSHA 1981)], these systems allow the user to hear ambient communication and environmental sounds at the same level as they would if the ears were unoccluded. When ambient noise levels exceed 85 dB (A), the system limits or compresses the transmitted level, thus protecting the user. The actual level under the HPD depends, however, on the amount of noise that is not passively attenuated by the HPD as well as the level of amplification selected by the user. Therefore, measurements were also made for the input-output function of the SA microphones of the EMs and EPs as a function of the amplification setting (off, L1–L7) and noise level [75–110 dB (A)].

3.1 Facilities and Instrumentation

3.1.1 Research Facility and Loudspeaker

A pink noise test signal was presented from a Meyer Sound MSL-4 Horn-Loaded Long-Throw loudspeaker paired with a 700-HP UltraHigh-Power Subwoofer located at the end of the Distance Hall at EAR (Henry et al. 2009) facility (Fig. 19a).

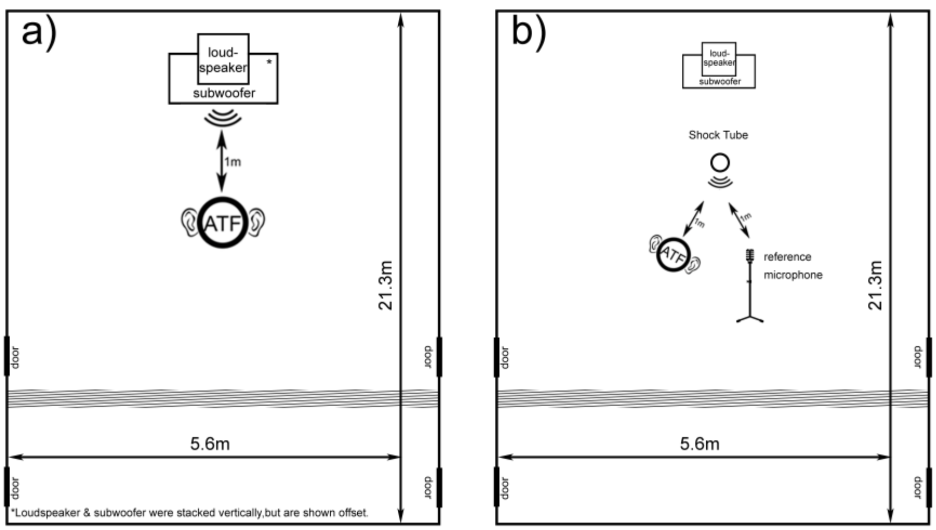

Fig. 16 Schematic of test setup used for the continuous noise attenuation measurements. The ATF was rotated in 30° increments to each of the positions indicated by the markers in the shaded region

3.1.2 Noise Signal

A Larson-Davis SoundTrack LxT Class-1 sound-level meter (SLM) was used to measure the sound levels in the room. Sound levels were calibrated by adjusting the digital mixer values until the SLM (A-weighted/slow setting[4]) matched each of 8 target levels [75, 80, 85, 90, 95, 100, 105, and 110 dB (A)] and noting the digital setting required to produce that level. These settings were then used for all testing.

3.1.3 ATF and Reference Microphone

The same G.R.A.S. 45CA ATF used for the measures of directional attenuation was used to measure SA microphone transmission.

A G.R.A.S. 40BH 0.25-inch microphone was used as a reference when measuring the input-output functions. This allowed the data to be corrected for minor variations from the target ambient noise level. It also allowed us to estimate the transfer function of the ear canal of the ATF.

3.1.4 Analog to Digital Conversion

The microphones' analog outputs were transmitted via an RME Octamic II MADI preamplifier and through the Peavey MediaMatrix NION digital audio network to the computer in the EAR Control Room, where they were recorded using Adobe Audition 3.0 software.

3.2 Variables

The dependent variable for the SA microphone input-output testing was the level (A-weighted decibels) as recorded by the ATF under the HPD as a function of: signal presentation level [75–110 dB (A)] and gain setting (off, L1, L2, L3, L4, L5, L6, and L7). Measurements of the dependent variable were made for all levels of the independent variables for both the EPs and the EMs.

3.3 Procedures

The same procedure described in Section 2.3 was used to calibrate the ATF. The reference microphone used for the SA microphone transmission measures was calibrated using the same calibrator (using a standard 0.25-inch coupler).

To obtain the noise levels under the HPD, the ATF was fitted with the HPD, the gain was set to one of the 8 SA settings (off, L1, L2, L3, L4, L5, L6, and L7), and the mixer was set to the level required to achieve one of the target levels (75, 80, 85, 90, 95, 100, 105, and 110 dB). A 5-s recording was made. This process was repeated for each of the target levels and each of the 8 SA settings until the recordings were complete.

3.3.1 Data Analysis, Results, and Discussion

3.3.3.1 SA Microphone Transmission

There were minor variations in the actual target levels achieved (as recorded by the reference microphone). The data reported here have been adjusted by correcting the levels measured by the ATF by the difference between the target signal level and that measured by the reference microphone [target signal level = 85 dB (A), reference microphone level = 84.8 dB (A), and reported data = ATF level + 0.2 dB (A)].

Figure 20 shows the measured levels for the a) EMs and b) EPs for each measured active SA setting and each level of noise. The passive, “off” condition is shown as a blue line. A dotted vertical line indicates the location of the 85-dB (A) trigger. A dotted horizontal line shows the same 85-dB (A) limit that the measured levels purportedly should not exceed. Both the EMs and EPs show a bend at 85 dB (A), indicating that the electronics are beginning to compress the input signal when the level exceeds 85 dB (A). The mechanism is compression, as the input is not completely shut off (it would only be at the passive level, if so) but rather is reduced. The amount that the signal is compressed increases as the input signal is increased so that at 110 dB (A), the level is just slightly more than that measured with the SA microphones turned off.

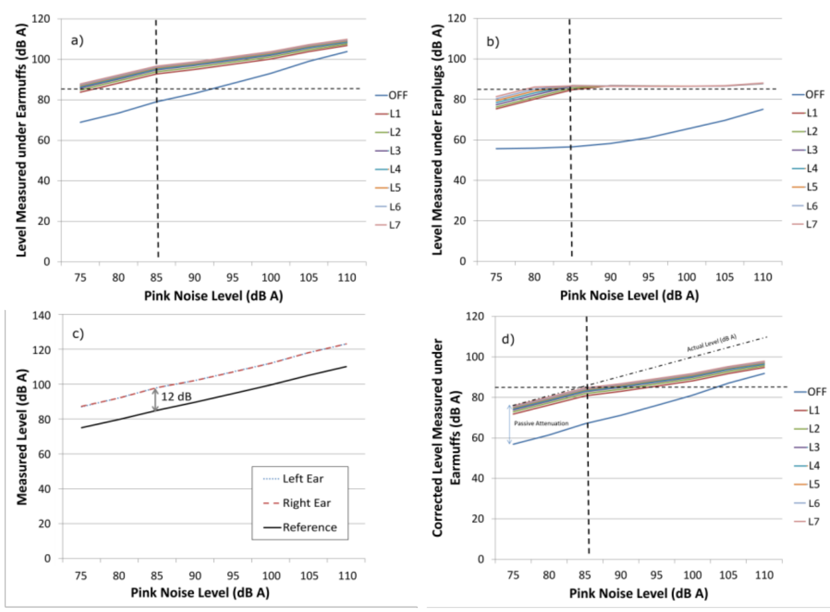

Fig. 17 The input-output functions measured for a) EMs and b) EPs as a function of SA microphone setting, c) the transfer function derived by comparing the levels measured with a reference microphone and the same levels measured with the ATF when no HPD was used, and d) the input-output function of the EMs “corrected” by subtracting the transfer function of the ATF

As noted in the directional measurements, the EMs do not attenuate as much as the EPs. The level under the headset is well above 85 dB (A) before compression begins. This might be explained by the transfer-function of the ear canal. Clearly, the level under the EM is greater than the level measured by the reference microphone, suggesting that the ear canal is amplifying the signal slightly. Figure 20c shows the measurements made for the reference microphone and the ATF without hearing protection. There is approximately 12 dB of difference between the 2 signals. If this 12 dB is subtracted from the level measured under the EMs (Figure 20d), the level more clearly matches that of the EPs. The SA microphone amplification settings allow the user to increase the level about 8–10 dB, roughly a 2:1 gain.

The EPs do an excellent job of keeping the level at the ear under 85 dB (A); at 110 dB (A), the noise level under the EPs was only 88 dB (A) for the highest microphone setting. For EMs, attenuation was limited to approximately 18.5 dB (A) of passive protection. With the microphones on the highest setting, the level under the EM at 110 dB (A) was 110 dB (A). Given that EPs also can seal better than the EMs, preventing the transmission of external noise, they may reduce its interference when communicating via radio. The spectral profiles of the EM and EP transmission differ significantly, and it is clear that the signal has been optimized for use with an EP in that the spectral range normally amplified by the ear canal has been amplified for the listener. From a human factors standpoint, it is important to note that the user must insert EPs correctly to get this protective seal, whereas with EMs it is less difficult to don them correctly.

4. Impulsive Noise Attenuation

We tested the EMs and the EPs for their attenuation of impulsive noise. Both devices were tested with the SA microphones set in the off, on low (L1), and on high (L7) settings and with impulse levels of 150- and 171-dB peak levels.

4.1 Facilities and Instrumentation

4.1.1 Research Facility and Impulsive Noise Source

All impulse noise measurements were made in the EAR Distance Hall (Figure 19b). A pneumatic impulse noise source (PINS) was used to present impulsive noises for measurement. By adjusting the distance between the PINS and the microphones from 4 to 0.5 m, we were able to reliably generate impulses that were measured by the reference microphone as having 150- and 171-dB peak levels.

4.1.2 ATF, Reference Microphone, and Recording System

The same G.R.A.S. 45CA ATF used for the measures of directional attenuation was used to measure impulse noise attenuation.

A G.R.A.S. 40BH 1/4-inch microphone was used as a reference when measuring the input-output functions. This allowed the data to be corrected for minor variations from the target ambient noise level. It also allowed us to estimate the transfer function of the ear canal of the manikin. The reference microphone and ATF were 1 m apart at the same distance from the PINS (Fig. 19b).

An Echo Audiofire 12 recording interface set to a sampling rate of 192 kHz was used for analog to digital conversion and to transmit the signal to a laptop computer where it was recorded using Adobe Audition 3.0.

4.2 Calibration

A 114-dB 250-Hz calibration signal was recorded with each ATF microphone and the reference microphone to establish the reference level. Simultaneous recordings were made of 2 instances of impulsive noise using the microphones of the ATF (unoccluded ears) and the reference microphone. These recordings were used to estimate the transfer function of the ear canal. From these recordings it was determined that the left and right ears of the ATF contribute amplifications of 4.87 and 4.68 dB, respectively, due to resonance in the ear canal (Shaw 1974).

Attenuation was computed as the difference between the peak level measured by the ATF (the left and right ear each contributed separate data points) and the peak level measured by the reference microphone minus the transfer function for that ear.

4.3 Testing Procedure

The HPD was positioned on the ATF and a recording of the PINS-generated impulse noise was obtained from the microphones of the ATF and the reference microphone. This process was repeated 3 times for each HPD [EMs, EPs, and both] in each SA microphone condition [off, on low (L1), and on high (L7)] and for each test level [150- and 171-dB peaks]. The HPD was removed and refitted between each measurement.

4.4 Data Analysis, Results, and Discussion

The average impulse attenuation was computed for each of the test conditions and shown in Fig. 21. Figure 21a shows the results grouped by hearing protector type to allow for comparison of SA microphone settings. Figure 21b groups the results by SA microphone to facilitate comparison of the hearing protector types. It is clear from Figure 21a that the electronic shut-off is being triggered, as there is less than a standard deviation between the different microphone settings. Similarly, the difference between the impulse noise protection provided by the EPs and the double hearing protection conditions is not of practical importance. The EMs provided at least 23 dB of attenuation in all conditions. The EPs and double hearing protection conditions exceeded the bone conduction threshold. Slightly greater attenuation was observed for the EPs and double hearing protection conditions when exposed to higher impulse noise levels. This effect has been observed in other measurements of impulse noise protection (Nakashima et al. 2006); it generally appears that attenuation is nonlinear, increasing somewhat as the impulse level increases.

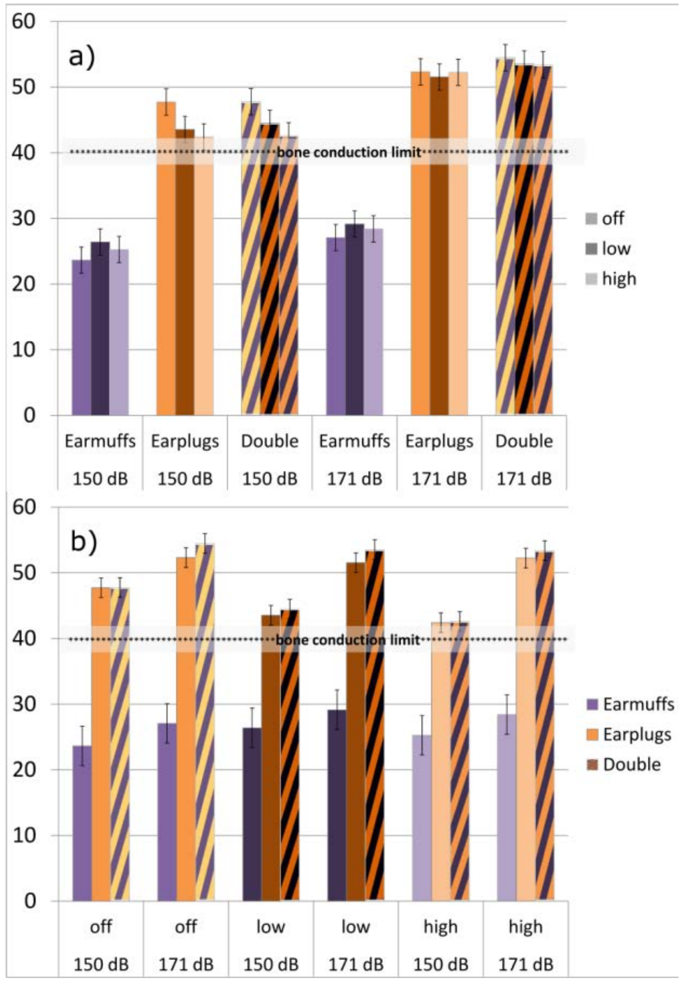

Fig. 18 Hearing protector attenuation measured with the SA microphones off, on low, and on high for 150- and 171-dB peak impulse signals: a) measurements grouped by hearing protector type for comparison of SA microphone effects and b) measurements grouped by SA microphone setting for comparison of hearing protector type

5. Summary and Conclusions

Two candidate HEaDS-UP helmet systems (CIPHER helmet, INTERCPT helmet, and mandibles), and their accompanying Selex Wolverine tactical communications headset options (EMs, EPs, and combined double protection) were evaluated for their effects on auditory SA and their ability to protect the listener. Since the systems are modular and reconfigurable, they were evaluated in all relevant configurations with the exception of a few instances where it was not possible to obtain consistent measurements.

Measures of the directional attenuation of steady-state noise documented spectral changes as a function of helmet and hearing protection use. When worn without the mandible and eyewear components, the helmets' attenuation measures were similar to those of the currently fielded ACH. Adding the mandible and eyewear components increased this attenuation slightly. Directional effects were observed in the spectral profiles of the recordings made for each helmet/HPD condition, which likely drive differences in auditory spatial orientation capabilities.

Measurements of the input-output function of pink noise, presented at 5-dB increments from 75 to 110 dB (A) for HPDs in both the passive and each of the 7 active SA microphone settings, suggest that the headsets begin to limit the transmission of the SA microphones when the ambient levels reach about 85 dB (A). When the SA microphones are turned on high (L7), they provide about 8–10 dB of amplification. For the highest amplification setting, and because of no passive attenuation of ambient noise, levels reached 110 dB (A) under the EM for ambient levels of 110 dB (A).

The HPD systems (EMs, EPs, and double hearing protection) provided impulse noise protection equivalent to that of passive protection regardless of whether the SA microphones were on and amplification was set to the lowest or the highest amplification setting. Impulse attenuation increased as the level of noise increased.

Generally the systems performed well, as intended. There were some concerns about the fit of the headsets on the auditory test fixture when positioned under the helmet. Without either visual or proprioceptive feedback about whether the headsets moved during placement of the helmet, it was difficult to be sure that the measurements were accurate. Another concern was the general inflation of the attenuation estimates obtained for the EPs worn on the ATF. From a practical standpoint, these measurements can only be taken as evidence that in the passive SA microphone condition these EPs perform similarly to other EPs and better than the EMs.

It was interesting to observe that the signals from the EPs and the EMs are filtered differently. This filtering seemed quite appropriate for the EPs, in that it replaces resonance that is lost by inserting the plugs into the ear canal. However, the overall hearing restoration levels ended up being much lower than that measured for the EMs. It was unclear whether this was intentional or simply due to the fact that more noise may have been leaking under the seal of the EMs, thus resulting in higher levels for the EMs. These higher levels may also be needed for the EMs due to higher levels of noise masking.

6. References

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7. Notes

1. A-weighted decibels, abbreviated as dB (A), are an expression of the relative loudness of sounds in air as perceived by the human ear. In the A-weighted system, the decibel values of sounds at low frequencies are reduced compared with unweighted decibels, in which no correction is made for audio frequency. This correction is made because the human ear is less sensitive at low audio frequencies, especially below 1,000 Hz, than at high audio frequencies.

2. It is quite possible that a user of this system would be able to assess the fit of the plugs and adjust them more easily under the manikin (which had a hard surface). A wireless configuration would eliminate this problem.

3. The NRR for the 3M Peltor ComTAC (a similar tactical EM) is 22 dB. The NRR for the Comply Foam tips used with the EPs has an NRR of 29 dB.

4. "Slow setting" refers to the time interval over which the sound pressure level is averaged during measurement. "Slow" is defined as a 1-s averaging window in contrast to the much shorter 125-ms averaging window of the "Fast" setting. Since the noise source is a steady-state noise, this gives the most reliable estimate of level.

List of Symbols, Abbreviations, and Acronyms

ACH	advanced combat helmet
ATF	auditory test fixture
CIPHER	Conformal Integrated Protective HEadgeaR
EAR	Environment for Auditory Research
EM	earmuff
EP	earplug
HEaDS-UP	Helmet Electronics and Display System-Upgradeable Protection
HPD	hearing protection device
INTERCPT	INTEgRated Conformal Protective helmeT
ME	mandibles or eyewear
NRR	noise-reduction rating
PINS	pneumatic impulse noise source
SA	situational awareness
SLM	sound-level meter

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